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PROJECT SUMMARY

Project Title: Flywheel Testing and Evaluation

Principal Investigator: R. S. Steele

Organization: Oak Ridge Y-12 Plant
Union Carbide Corporation, Nuclear Division
P.O. Box Y
Bldg. 9998, MS-2
Oak Ridge, TN 37830
(615) 574-1838

Project Goals: The objective of the testing program is to evaluate the performance of composite flywheels developed under the flywheel rotor and containment technology development project. The evaluations will determine the performance limiters in both ultimate energy storage and life under cyclic fatigue loading.

Project Status: Test data to date supports six general statements regarding the state-of-the-art regarding flywheel development.

a. Energy density performance exceeds metallic flywheels performance.
b. Containment requirements are less severe.
c. Fatigue life typically exceeds 1000 cycles.
d. Thermal considerations dictate low pressure environments.
e. Suspension system design must consider balance changes with speed.
f. Analytical models of the flywheels have increased confidence.

Testing supports the early proponents' predictions of composite flywheels' applicability. But the data also show that the risk of using this new technology may still be high. Composite flywheels have demonstrated energy density and total capacity sufficient to accomplish the automotive energy storage requirements. Testing must now address questions relating to lifetime, reliability, system design, and cost.

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FLYWHEEL TESTING AND EVALUATION*

R. S. Steele
Oak Ridge National Laboratory**
Oak Ridge, Tennessee 37830

ABSTRACT

During the past several years, the DOE Mechanical Energy Storage program has supported spin testing of high performance composite flywheels to verify analytical predictions, identify unknown parameters, and understand the factors influencing flywheel reliability. In general, the results have supported the early predictions of flywheel performance; but certain real world factor evaluations now require further investigation. This paper discusses six general statements regarding the state-of-the-art in composite flywheels technology and presents the supporting data. (1) Composite flywheel performance is superior to that of metallic flywheels, while (2) presenting less severe containment requirements. (3) Composite flywheel fatigue life exceeds 1000 cycles. (4) Thermal considerations dictate a low pressure environment. (5) Balance characteristics of composite flywheels require special suspension provisions. And finally, (6) analytical models predict performance with increasing confidence and are thus becoming more useful in establishing the reliability of the rotor. Testing efforts must now address questions relating to lifetime, reliability, system design, and cost.

Introduction

Verification of analytical predictions, identification of unknown parameters, and the need to understand the factors influencing reliability of composite flywheels require comprehensive evaluation of prototype candidates. During the past several years, testing of this type has given much useful information regarding the performance characteristics of the designs developed under the DOE Mechanical Energy Storage Program. Strong statements regarding the performance and reliability of composite flywheels will need much more data than currently exists, but general trends are identifiable. These trends generally confirm the expectations of the early proponents, who now find credible support in the available data.

The data presented in this paper draw largely from the testing done at the Oak Ridge Flywheel Evaluation Laboratory (ORFEL) and the Applied Physics Laboratory (APL). Additional data come from tests at Garrett AiResearch, Rockwell Rocketdyne, and others.

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** Current address Oak Ridge Y-12 Plant

These data lead to the following statements regarding the performance characteristics of composite flywheels:

a. Energy density performance exceeds metallic flywheels performance.
b. Containment requirements are less severe.
c. Fatigue life typically exceeds 1000 cycles.
d. Thermal considerations dictate low pressure environments.
e. Suspension system design must consider balance changes with speed.
f. Analytical models of the flywheels can be used with increased confidence.

The remainder of this paper will discuss each of these topics and present its supporting evidence.

Performance of Composite Flywheels

The past year's activities added several more points to the list of flywheel energy storage achievements. Figure 1 shows the learning curve for energy density since 1973 for composite flywheels storing greater than 0.250 Wh. The trend seen resulted from experience gained by the flywheel designers under the continuing support of the DOE. The current performance leaders are Garrett's high energy density flywheel at 80 Wh/kg and their high capacity DOT bus flywheel. A single section of this latter rotor has stored 3 kWh, and a stack of six of these rotors will soon store 16 kWh.

Efficient use of material is another category for consideration, since it relates so closely to rotor cost. This factor of merit resembles the shape factor used in the early selection of rotor designs but includes the real effects of actual design and fabrication performance. One calculates the design factor by dividing the energy density achieved in tests by the weighted average strength to density ratio of the material used. Table 1 gives the design factor for a number of rotors evaluated during the past several years. Owens Corning Fiberglass has the current best design factor with their chopped glass SMC disk with graphite support ring.

Containment Requirements

Composite flywheels have less severe containment requirements than metallic rotors for two reasons: designed-in benign failure modes and/or crushable fragments. The Garrett sub-circular rim demonstrated a benign failure mode when its ultimate speed was found to be limited by dynamic instability associated with rim circularity. Figure 2 shows the increasing circularity of this flywheel as the speed increased. The experience with the thick-ring designs of Union Carbide Corporation, Hercules, and others demonstrates another well-known type of benign failure. These circumferentially wound cylinders experience circumferential cracking resulting in pressure increases and minor balance changes. Either may be used as a noncatastrophic damage warning.

Containment requirements are also less severe, since catastrophic failures produce either stringy masses or crushable fragments. This is a direct consequence of the low transverse strength in the composites, as has been shown sufficiently in previous papers [1, 2, 3].

Adequate containment has now been shown to require more than prevention of simple penetration. Tests to date show the need to consider torque [4] as a major design factor and, in addition, explosions resulting from gas released by the decomposing composite during failure or by dust ignition should oxygen, entering the cavity during the failure, mate with the heat and ground fibers. The containment design [5] currently pursued by the Mechanical Energy Storage Project and scheduled for testing in FY 1983 addresses each of these items as a direct result of the observations made during the flywheel burst tests.

Fatigue Life of Composite Flywheel

Successful application of a composite flywheel assumes an adequate cyclic fatigue life. Only three fatigue tests involving composite flywheels provide directly applicable data. This year an alpha-ply disk with a graphite rim was cycled 1,454 times until failure, not believed associated with the composite, terminated the test. Previously, Garrett cycled their NTEV-2 composite rim with an aluminum hub to 106% of the operating speed 1,000 times as a proof test. They have also performed a similar test on a 3 kWh module of their DOT bus flywheel for 638 cycles. Neither flywheel failed.

The use of composite materials is in its early development. Thus, the necessary understanding needed to extrapolate accelerated or proof testing to estimates of life at the intended operating condition has low statistical confidence and is subject to considerable controversy. Thus, this year's activities include cycle testing of a GE disk rotor and a Garrett sub-circular rim rotor at near-operating conditions until a failure results. These tests will demonstrate whether adequate cycle life is available as well as start a data base for developing the analytical model needed for extrapolation.

Thermal Management and Pressure Requirements

The predictions of pressure requirements need definitive experiments for verification. The prediction by M. R. Baer [6] indicates maintenance of less than 66 C will demand a cavity pressure of less than 1 millitorr. The Rockwell Rocketdyne flywheel test experience illustrates the problem. This rotor was spun for approximately 2h at peripheral speeds up to 732 m/s and pressures up to 10 millitorr; the maximum temperature reached only 25 C. The same flywheel, tested in similar manner but at a chamber pressure of 1000 millitorr, reached a temperature in excess of 120 C at the time a portion of the rim was slung off.

Definitive experiments are needed and will require that a flywheel spin at a constant speed long enough, possibly over 10 hours, to reach thermal equilibrium at different pressures. The goal will be to verify the analytical models and to provide input as to any detrimental affects thermal energy produce.

Rotor Balance Experience

Muske and Flores [7] found in their survey of industrial balancing practice that items in the composite flywheel class are typically balanced to a mass eccentricity of less than 7.5 micrometers. Table 2 gives a summary of our balance experience in ORFEL and shows that the as-received flywheels would all require additional balancing to meet this specification. Thus, any cost analysis must include the expensive process of close tolerance balancing.

Whether or not balancing was possible did not concern rim type flywheel developers since the inside diameter of the rim provided a natural place for the balance weight. Disk type flywheel developers were less certain, since weights could not be bonded with confidence to the planer surfaces and the consequences of drilling holes near the outside diameter was unknown. Tests this year have now shown that the use of balance holes in both the SMC molded disk and the alpha-ply layup disk flywheels do not reduce performance. Figure 3 shows flywheel OCLB after balancing with this method.

Composite flywheels' tendency to change their balance as the spin speed and gyroscopic stresses change causes more concern. Table 2 shows the differing degrees at which various flywheels are affected. The phenomena appears worse in spoke-supported rims than in disk types; but even in the disk types, the design of the suspension system must consider the phenomena.

Increased Confidence in Performance Predictions

Confidence in performance predictions has increased significantly in the last several years. It results from improved fabrication of composite material, a growing maturity in the analysis of and for the failure mode, and an improved ability to test for a particular failure mode. The best example of this is given in Figure 4 showing the predicted and actual performance achievements of the Owens Corning SMC disk with several different supporting rings.

Conclusions

The testing to date supports the early proponents' predictions of composite flywheels' applicability. However, the data also show that the risk of using this new technology may still be high. Composite flywheels

have now demonstrated energy density and total energy capacity sufficient to accomplish the automotive energy storage requirements. We must now address questions relating to lifetime, reliability, system design and cost.

References

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Table 1. Design factors for rotors tested for ultimate storage capacity

Manufacturer	Wheel Type	Material[a]	Burst energy[b] (wh/kg)	σ/ρ (wh/kg)	Closest Rotor K factor	Design Factor (K')
Brobeck	Rim	SG/K49	63.7	340.2[d]	0.44	0.20
Garrett/ AiResearch	Rim	K49/K29/SG	79.5	317.4[d]	0.44	0.23
Rocketdyne	Overwrap rim	G	36.1	274.2	0.44	0.13
APL-metglass	Rim	M	24.4	91.2	0.44	0.27
Hurcules	Contoured pierced disk	G	37.4	274.2	0.47	0.14
AVCO	Pierced disk	SG	44.0	262.6	0.35	0.17
LLNL	Tapered disk	G	62.6	274.2	0.80	0.23
LLNL	Flat disk	SG	67.1	262.6	0.61	0.26
GE	Solid disk	SG/G	55.1	263.7[e]	0.61	0.21
Owens/Lord	Disk	SMC/G	27.8	95.0[e]	0.61	0.29
		SMC/G	36.6	115.0[e]	0.61	0.32
		SMC/G	25.0	62.71[e]	0.61	0.39
		SMC	17.5	43.8[e]	0.61	0.40

[a]Material legend is: SG = S Glass; K49 = Kevlar 49; K29 = Kevlar 29; G = Graphite; M = Metglass; SMC = S-glass sheet molding compound

[b]Burst tests results as reported by DOE Mechanical Energy Storage Technology Program

[c]Calculated as follows: $K' = BE/(\sigma/\rho)$.

[d]Assumes higher σ/ρ material at outer part of rim is limiting factor.

[e]Proportioned by weight.

Table 2. Summary of balance data taken from tests performed at ORFEL

Rotor	Mass (Kg)	OD (m)	Mass Eccentricity at 200 H_z (μm)	Mass Shift Speed Range (Hz)	Mass Shift Distance (μm)	Out-of Plane Angle (μrad)	Hub Attachment Type
UCCND-2	11.15	0.508	13[2]			636	Spokes
-3	7.17	0.467	53	200 to 400	129	694	Spokes
-4	7.17	0.467	25			1631	Spokes
-5	7.17	0.467	--[3]			500	Spokes
SLA	10.70	0.508	178[3]			1069	Spokes
WMB-1	11.79	0.350	46	200 to 500	45	844	Spokes
G-1[1]	15.55	0.584	23	200 to 400	46	-[3]	Spokes
H-1[1]	22.67	0.589	83	100 to 300	15	148	Disk
R-1	53.74	0.305	11	100 to 300	12	-[3]	Disk
LLNL-1[1]	5.88	0.610	121	200 to 500	3[4]	233	Disk
GE-1[1]	10.88	0.450	180	100 to 500	3[4]	879	Disk
LLNL-2	-[3]	-[3]	103			-[3]	Disk
OCLA	12.91	0.616	3148			485	Disk
OCLB	10.95	0.560	881	100 to 300	58	144	Disk
OCLC	14.59	0.614	868	100 to 300	218	500	Disk
OCLD	9.90	0.534	513	100 to 300	172	1160	Disk
GEB	10.08	0.450	200	100 to 400	75	498	Disk
GEC	10.35	0.400	278	100 to 500	51	896	Disk

[1]Rotors were not balanced. [2]Rotor was dynamically balanced prior to receipt. [3]Measure is unavailable. [4]Disk only, does not include shift due to elastomerically bonded hub. [5]Maximum speed not limited by material.

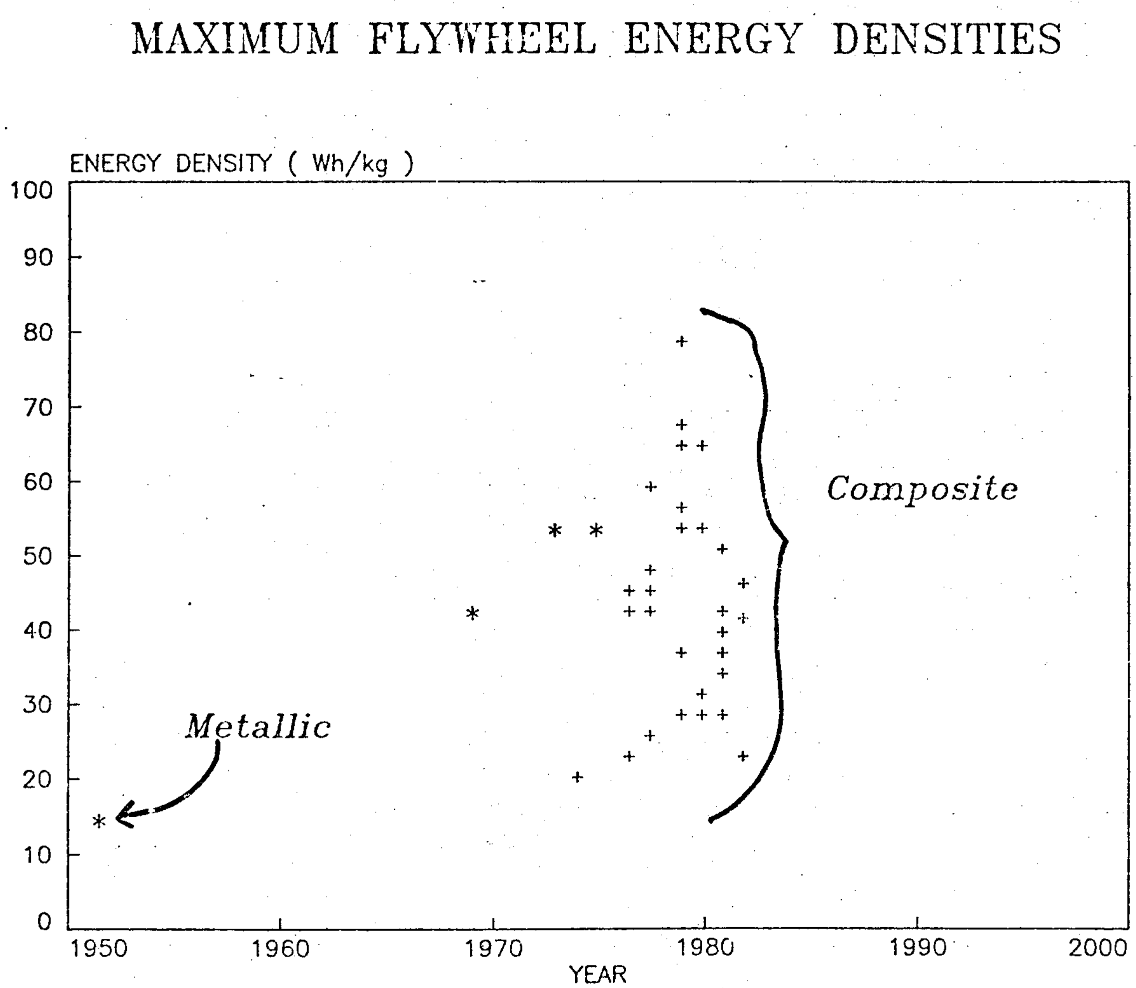

Figure 1. Maximum energy density achieved at ultimate speed with composite flywheels storing greater than 0.250 kWh exceeds the best metallic flywheel performance.

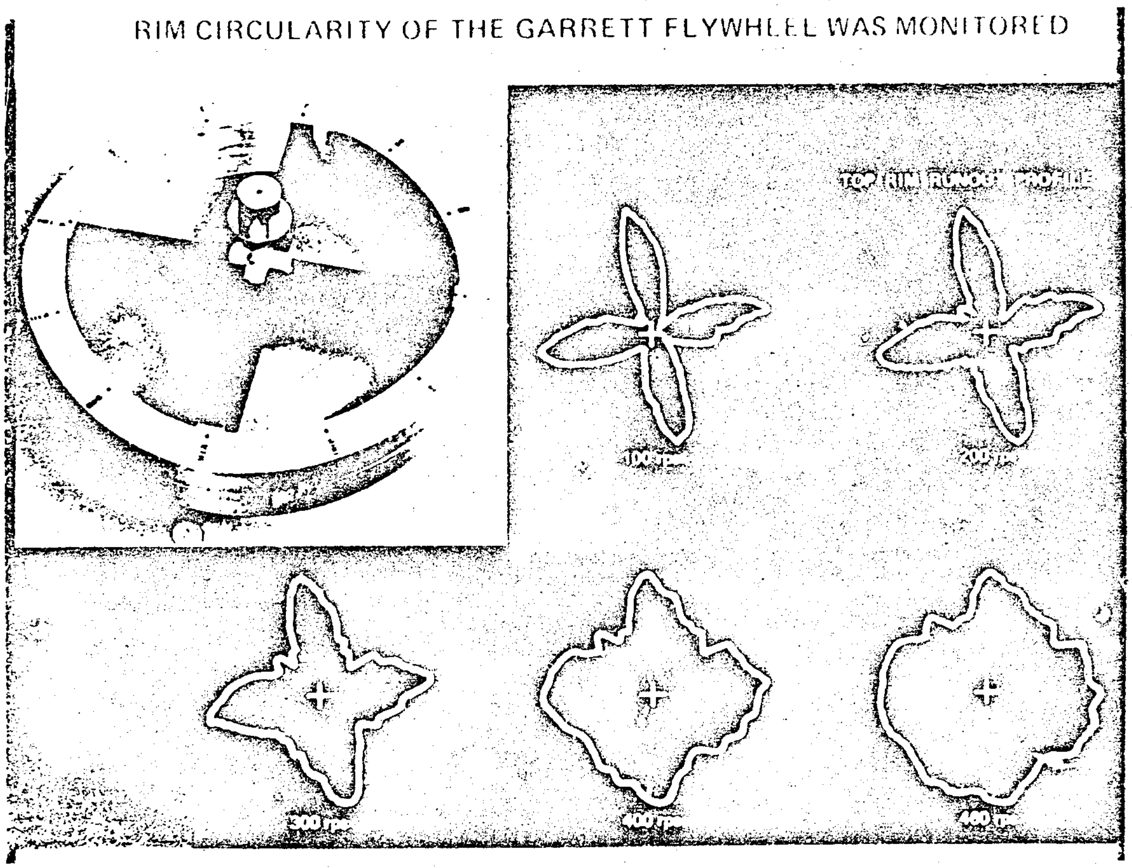

Figure 2. Garrett sub-circular rim has four distinct lobes. Ultimate speed is determined when rim becomes circular.

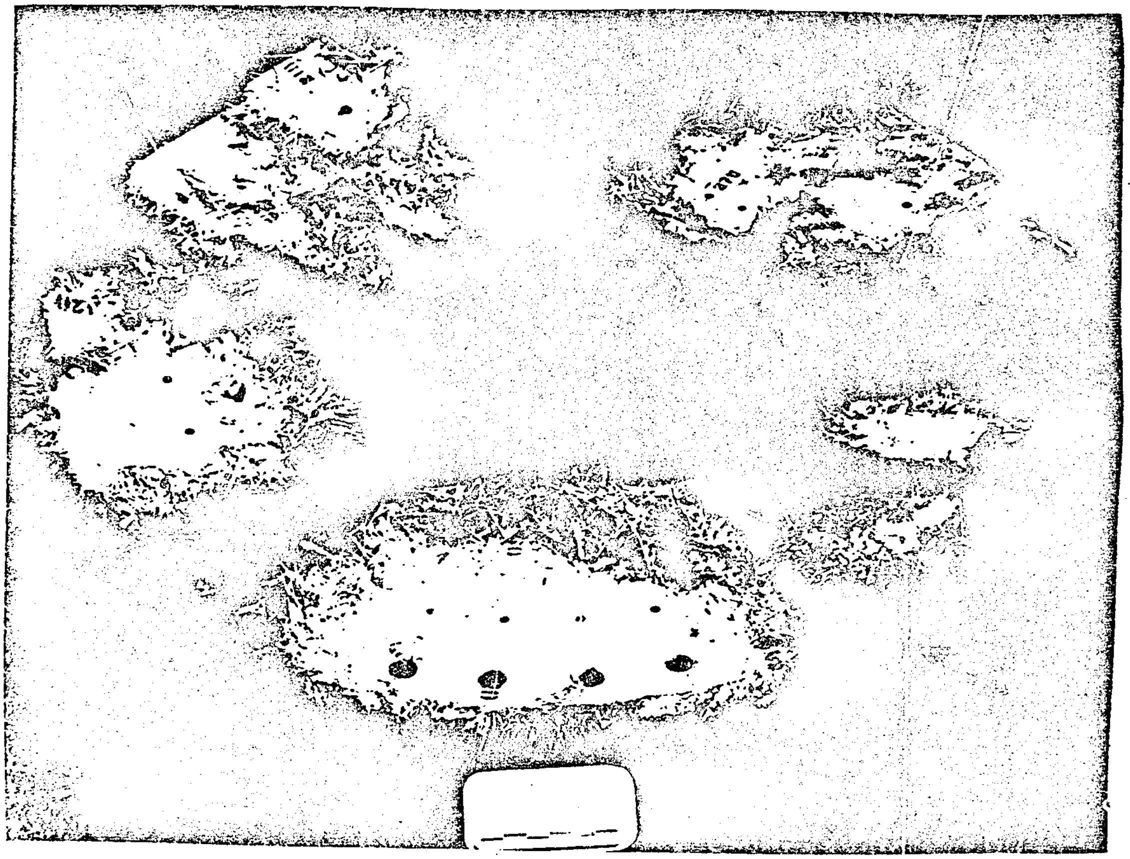

Figure 3. Balance holes found in wreck debris of OCLB do not appear to have influenced the failure mode.

PERFORMANCE OF OWEN'S CORNING/LORD FLYWHEELS

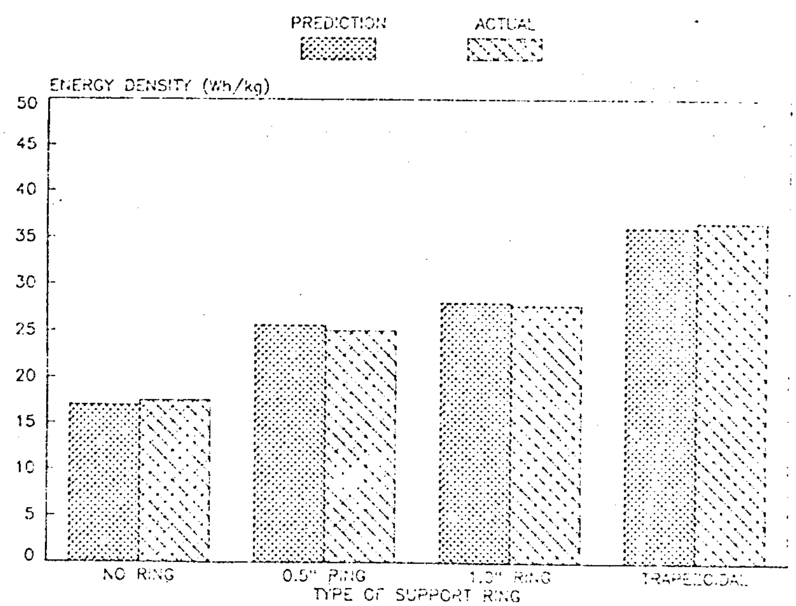

Figure 4. The ability to predict the performance of composite flywheels was demonstrated in the OCL series of flywheel evaluations.